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PULSARS

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ABSTRACT

In this paper the general properties of Pulsars are reviewed. The identification of pulsars as magnetized neutron stars is one of the most exciting discoveries in astrophysics in recent years. Much of the physics of neutron stars are still unknown; the properties of neutrons at densities beyond 10^{14} g/cm^{3} are in the frontier land of particle physics. However, as long as the radiation mechanism is not known, little can be correlated between the rich data and the properties of neutron matter.

Pulsars were discovered by Hewish et al.[1] in 1968 during a sky survey of scintilation phenomena due to interplanetary plasma in the radio frequency ~100 MHz. Among the expected random noises emerged "signals" timed at regularly spaced intervals, of periods ~1 second. These periods were soon established to an accuracy of 6 or 7 digits, making them one of the best determined astronomical constants outside the solar system.

Since the discovery of the pulsars many theoretical papers have been written on this and related subjects. Up to date the radiation mechanism remains still an unresolved subject. In this paper those interpretations of the properties of pulsars that will most likely survive the passage of time (in the author's opinion) will be discussed. The readers should beware of more recent developments in literature as this is still a very active subject of study.

1. Emission and Origin of Pulsars

One may safely state that all pulsars emit in the radio frequency range 20-10^4 MHz. Only one pulsar, NP0532, is known to emit in the optical, x-ray, and the γ-ray regions.* Around 60 pulsars have been discovered to date; the period of these pulsars vary between 0.033 sec and 3.5 seconds. The pulse shape, structure, polarization, intensity, and spectrum show great variations among different pulsars. For the same pulsar there are great temporal changes. The great variety of data made theoretical interpretations very difficult.

*The so-called x-ray pulsars are actually close binary systems and will not be further discussed in this paper.

The intrinsic radiation rate of pulsars in the radio spectrum ranges from 10^{29} to 10^{33} ergs/sec. From the estimated radiation area ($\sim 10^{12}$ cm^2) the calculated brightness temperature is many orders of magnitude higher than any conceivable black body temperature. Most likely a coherent maser like process accounts for radiation. However, coherent maser like radiation as we know emit in discrete wavelengths. A good radiation theory must account for the broadband nature of emission, as well as regularity in certain features of emission.

In general pulsars emit with a duty cycle less than 10%. A simple geometrical model of a pulsar is a highly collimated beam, in the shape of a search light beam or a fan, co-rotating with the object.

The pulsing nature of the emission can be detected only when the receiver bandwidth is small. This is caused by the effect of interstellar plasma on the propagation of electromagnetic waves. In a plasma the velocity of propagation v_p is frequency dependent:

$$v_p \approx (1 - \omega_p^2/2\,\omega^2)\,c \qquad (\omega_p \ll \omega) \tag{1}$$

where $\omega_p = (4\pi N e^2/m)^{1/2}$ is the plasma frequency in a medium of electron density N, ω is the angular frequency of radiation. The propagation delay Δt in term of the differences in velocities of propagation, and the distance ℓ, is

$$\Delta t \simeq \ell \, \Delta v_p / c^2 \tag{2}$$

In interstellar medium N varies between 0.01 and 1. As an example, over a distance of 10^3 light years for $\nu = 2\pi\omega$ at 10^8 Hz and 10^9 Hz, Δt may amount to 60 seconds if N = 0.01. Equation (2) enables one to determine the distance ℓ from the measured time delay, assuming that N is known or can be estimated. For all pulsars ℓ is less than 10^5 light years, and hence all pulsars are located within our Galaxy. Further, Eq. (2) applies to all pulsar emissions studied so far, including the optical and x-ray emissions of the NP0532 pulsar. It can thus be said that all radiations from pulsars originate from one common spatial region. Conversely, Eq. (2) has been used to obtain an upper limit of the photon mass ($\ll 10^{-44}$ g).

Detailed time structure studies of the fastest pulsar, NP0532, shows that rapid variations with time scales $\sim 10^{-4}$ sec exist. Since the size of the emission region must be smaller than the time scale of the fastest variation times the velocity of light, the region of emission is then less than 30 km.

Although pulsars exhibit great regularity in their periods, the periods of some of them have been found to be increasing at a rate $\Delta P/P \sim 10^{-12} - 10^{-16}$. The only rational interpretation to this increase in period is that the time keeping mechanism of the pulsars is rotation and as rotational energy is dissipated the period increases. In order for a star to be stable against a fast rotation as in NP0532, the radius of the star must be less than 100 km. This, coupled with the requirement that the emission region must be less than 30 km, and the association of the pulsar with a supernova remnant, implies that the pulsar must be a neutron star.

During a collapse process which transforms a star into a neutron star, conservation of angular momentum requires that the rotational angular velocity $\Omega \propto R^{-2}$. Therefore, even for a star like our sun with a moderate rotation (P $\sim$ 26 days), after a collapse which reduces its radius by a factor of 10^5 (from 10^{11} cm to 10^6 cm), the period will decrease by a factor of 10^{10}. The fastest rotational period of a neutron star is around 10^{-3} sec. During this collapse a number of the physical processes (e.g. ejection of matter) can decrease the angular momentum of the resulting neutron star so that this minimum rotational period is not violated.

The rotational energy of a neutron star of mass M, is fairly accurately estimated by the Newtonian expression:

$$E_r \sim \frac{1}{2} M R^2 \left(\frac{2\pi}{P}\right)^2 = 4 \times 10^{46} \left(\frac{M}{M_\odot}\right) \left(\frac{R}{10 \text{ km}}\right)^2 P^{-2} \text{ ergs} \tag{3}$$

where $M_\odot$ is the mass of the sun and P is the period in seconds. A increase in period dP requires the dissipation of rotational energy by an amount $2(dP/P)E_r$. In the case of NP0532, $dP/P = 5 \times 10^{-13}$, $P = 0.033$ sec. Hence

$$\frac{d E_r}{dt} \cong 6 \times 10^{38} (M/M_\odot) (R/10 \text{ km})^2 \text{ ergs/sec} \tag{4}$$

2. Neutron Stars and Magnetic Fields

Neutron stars were discussed by Landau as early as 1932, soon after the discovery of the neutron. In a dense electron gas the Fermi momentum P_F is related to the electron density N by the relationship

$$N = \frac{1}{3\pi^2} \lambda_c^{-3} (P_F/m c)^2 \tag{5}$$

At a sufficiently high density ($N \geqslant 10^{36}$ cm^{-3}, corresponding to a matter density of 10^{12} g/cm^3 if $z/A \sim 1/2$) the total Fermi energy of the electrons will exceed the total binding energy of the nuclei. Inverse beta process will eliminate most electrons and protons, and the predominant composition of matter is the neutron. A small fraction of matter exists in the form of electrons and protons and some nuclei (1-12% depending on the density) to prevent the decay of the neutrons.

Stable neutron stars exist in the density range 10^{12} to 10^{16} g/cm^3. The physics of neutron matter become unclear above a density of $\sim 10^{14}$ g/cm^3, due to a lack of knowledge of nuclear interactions and high order particle interactions. The general relativity parameter $\frac{GM}{RC^2}$ of neutron stars is of the order of 0.1 or greater. General relativity theory has a strong effect on the stability of neutron stars, in that the stress energy of the neutron matter contributes to the gravitational field thus causing a runaway type instability if the mass of the neutron star is too high. An instability occurs at $0.7\ M_{\odot}$ if interaction is neglected in the neutron gas. Uncertainties in the particle interactions may cause a change of the value of the instability mass but cannot eliminate this instability. Currently it is believed that no stable neutron stars exist beyond a mass of 3 or $4\ M_{\odot}$.

Magnetic fields of a neutron star may be as high as 10^{14} G. During compression of a plasma, magnetic fluxes are conserved according to the scaling relation $H \propto R^{-2}$. Thus, for a star with a nominal field strength ($\sim 10^2$ G) the field may be as high as 10^{12} G after it is compressed to the size of a neutron star. The presence of such a strong magnetic field is supported by several observational facts associated with the Crab Nebula and other pulsars.

First, in order to couple the rotational energy of a spinning neutron star strongly to relativistic charged particles, as in the case of the Crab Nebula, the star must possess an intense magnetic field. A rotating magnetic dipole radiates electromagnetic waves of the same frequency as rotation. The dissipation rate of rotational energy of a neutron star is

$$\frac{d E_r}{dt} = - \frac{\beta^2 \Omega^4 R^6}{c^3} f \tag{6}$$

where f is a scaling factor ~ 1, $\Omega = 2\pi/P$. Translating (6), into the measured quantity $\frac{d\Omega}{dt}$ and Ω, one obtains

$$I \Omega \dot{\Omega} \sim B^2 \Omega^4 R^6 c^{-3} \tag{7}$$

where I is the moment of inertia of the neutron star ($I \sim M R^2$). From (7) the magnetic fields of most pulsars is placed between 10^{12} and 5×10^{13} G. This dipole radiation, having a very long wavelength, can accelerate charged particles to relativistic energies, thus accounting for the origin of cosmic rays.

A spinning magnetized conductor in a vacuum will also have an external electric field for which $\underset{\sim}{E} \cdot \underset{\sim}{B} \neq 0$. At the surface of the conductor the normal components of $\underset{\sim}{E}$ will pull electron or ions off the surface, thus generating a magneto sphere. This magnetosphere may account for the supply of particles in the origin of cosmic rays.

Below the surface the structure of a neutron star is fairly complicated. At a density of 10^{14} g/cm^3, the remaining charge particles can condense into solid like structures, (as a result of minimization of the Coulomb interaction). The lattice structure corresponding to the minimum Coulomb interaction is the body centered cubic. The "melting temperature", or the temperature at which $kT \sim \hbar\omega_o$ where ω_o is the vibration frequency of the lattice, is around 10^{10}°K. The outer surface of a neutron star is thus composed of a solid crust. This conclusion is verified in the observation of the so-called star quakes. It has been observed for at least two pulsars, NP0532 and the Vela pulsar, that the period decreases abruptly by an amount $\sim 10^{-6}$ P (Vela) and 10^{-9} P (Crab). This is interpreted as the resettling of the outer crust of the star, resulted from the readjustment of the balance between centrifugal force of rotation, the hydrostatic pressure gradient and the gravitational field as the star slows down. A liquid layer can adjust continually but in the case of a solid crust the adjustment takes place abruptly in the fashion of "quakes".

The identification of pulsars as magnetized neutron stars is one of the most exciting discoveries in astrophysics in recent years. Much of the physics of neutron stars are still unknown; the properties of neutrons at densities beyond 10^{14} g/cm^3 are in the frontier land of particle physics. However, as long as the radiation mechanism is not known, little can be correlated between the rich data and the properties of neutron matter.

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